Bounds to dark photon model from invisible and semi-invisible meson decays

Alexey S. Zhevlakov* [1]

Based on: arXiv:2312.01703 and Phys. Rev. D**108** (2023) no.11, 115005 which were done in collaboration with D. V. Kirpichnikov and V. E. Lyubovitskij, S. Kuleshov and S. Gninenko

*Bogoliubov Laboratory of Theoretical Physics, JINR

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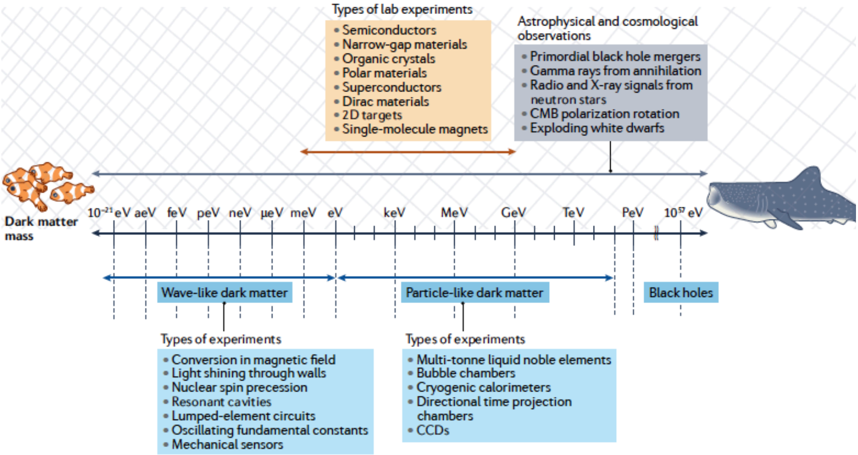
Outline

- Introduction
- Dark photon model and meson decays
- Bounds for dark photon model
- Conclusion

Dark matter puzzle



[Nature Reviews Physics vol 4, (2022)]

Fixed target experiments

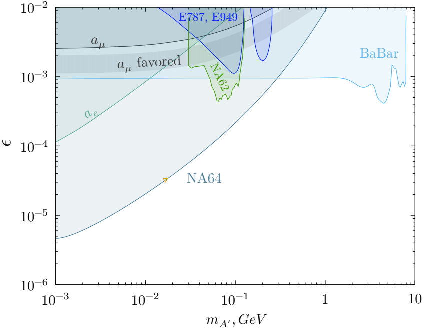
types of models

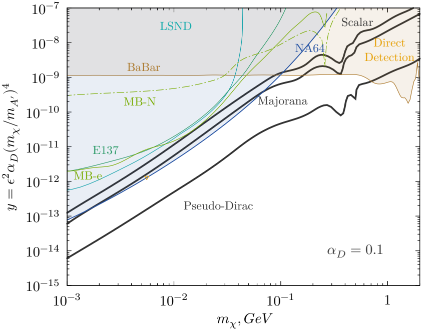
- General dark photon from kinetic mixing
- leptophilic, hadrophiic
- L_μ-L_τ
- etc.

Experiments

- with electron beam: NA64e, LMDX, ILC and etc.
- with muon beam: NA64μ, M^3
- with positron beam: NA64, ILC
- with proton beam: NA62, Coherent, REDTOP, HIAF and etc.

invisible mode A’





Background source	Background, n_b
1. Di-muons losses or decays in the target	0.04 ± 0.01
2. μ, π, K $\to$ e +... decays in the beam line	0.3 ± 0.05
3. lost neutrals (γ, n, K^0) from upstream interactions	0.16 ± 0.12
4. Punch-through leading n, K^0_L	< 0.01
Total (conservatively) n_b	0.51 ± 0.13

visible mode A'

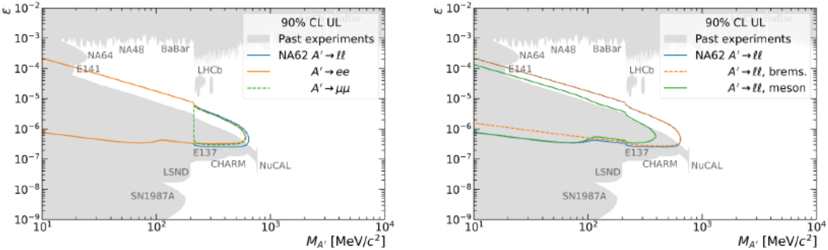


Figure 4. Regions excluded at 90% CL assuming zero events observed in the absence of background for meson decays or bremsstrahlung A' production, separated by decay mode (left panel) and by production mode (right panel). The grey underlying excluded regions are obtained using the DarkCast package [16] and results from ref. [17].

JHEP09(2023)035

Dark photon

The gauge invariant coupling of the dark photon A' and the SM photon A has the form

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F_{\mu\nu} A'^{\mu\nu} \tag{1}$$

where ϵ is the mixing parameter, $F_{\mu\nu}$ and $A'_{\mu\nu}$ are the stress tensors of the A and A' fields, respectively.
The interaction of the dark photon with the charged current of SM fermions and with dark fermion current has a form:

$$\mathcal{L} \supset \epsilon e A'_\mu J^\mu + g_D A'_\mu \bar{\chi} \gamma^\mu \chi \,, \tag{2}$$

where g_D is the coupling of the dark photon with dark fermions, e is the electric charge, and J_μ the electromagnetic current composed of the SM fermions.
The decay width of the A' to the dark fermions is

$$\Gamma_{A' \to \bar{\chi}\chi} = \frac{\alpha_D}{3} \, m_{A'} \, (1 + 2y_\chi^2) \, (1 - 4y_\chi^2)^{1/2} \,, \tag{3}$$

where $y_\chi = m_\chi / m_{A'}$, $\alpha_D = g_D^2/4\pi$, $m_{A'}$ and m_χ are masses of dark photon and dark fermions, respectively.

Vector meson decay into dark

We derive effective Lagrangian describing transition of neutral vector meson to dark photon

$$\mathcal{L}_{V-A'} \quad = \quad e\epsilon g_V m_V V_\mu A'^\mu, \tag{4}$$

The width of the decay of vector meson into the dark fermion pair $V \to \bar{\chi}\chi$ is given by

$$\Gamma(V \to \bar{\chi}\chi) = \frac{\alpha_D(\epsilon e)^2}{3} g_V^2 \frac{(m_V^2 + 2m_\chi^2)\sqrt{m_V^2 - 4m_\chi^2}}{(m_{A'}^2 - m_V^2)^2 + \Gamma_{A'\to\bar{\chi}\chi}^2 m_{A'}^2}\,, \tag{5}$$

where $m_{A'}$ and m_χ are the masses of intermediate dark photon and DM fermion, respectively, m_V is the mass of vector meson [Schuster:2021]. Here we use the Breit-Wigner propagator for the dark photon A' assuming that its total width is dominated by the $A' \to \bar{\chi}\chi$ mode.

Pseudoscalar meson decay into dark

The decay widths of the π^0 into $\gamma\gamma$, $\gamma A'$, and $A'A'$ are given by

$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{\alpha^2}{64\pi^3} \frac{m_\pi^3}{F_\pi^2}, \tag{6}$$

$$\Gamma(\pi^0 \to \gamma A') = \frac{\alpha^2\epsilon^2}{32\pi^3} \frac{m_\pi^3}{F_\pi^2} \left(1 - \frac{m_{A'}^2}{m_\pi^2}\right)^3, \tag{7}$$

$$\Gamma(\pi^0 \to A'A') = \frac{\alpha^2\epsilon^4}{64\pi^3} \frac{m_\pi^3}{F_\pi^2} \left(1 - \frac{4m_{A'}^2}{m_\pi^2}\right)^{3/2}. \tag{8}$$

$$\Gamma(\eta \to \gamma A') = \frac{9\alpha^2\epsilon^2}{16\pi^3} m_\eta^3 \left(1 - \frac{m_{A'}^2}{m_\eta^2}\right)^3 \left[\frac{C_8 \cos\theta_0}{f_8 \cos(\theta_8 - \theta_0)} - \frac{(1 - \Lambda_3) C_0 \sin\theta_8}{f_0 \cos(\theta_8 - \theta_0)}\right]^2, \tag{9}$$

$$\Gamma(\eta' \to \gamma A') = \frac{9\alpha^2\epsilon^2}{16\pi^3} m_{\eta'}^3 \left(1 - \frac{m_{A'}^2}{m_{\eta'}^2}\right)^3 \left[\frac{C_8 \sin\theta_0}{f_8 \cos(\theta_8 - \theta_0)} + \frac{(1 - \Lambda_3) C_0 \cos\theta_8}{f_0 \cos(\theta_8 - \theta_0)}\right]^2, \tag{10}$$

η/η' meson decays

Eur. Phys. J. C 31, 525–547 (2003) [M. Benayoun, P. David, L. DelBuono, Ph. Leruste, H.B. O'Connell]

Decay with intermediate vector meson:

$$\Gamma(\eta' \to (\rho^0 \to A')\gamma) = \frac{\alpha\epsilon^2}{8m^3_{\eta'}} g^2_{\eta'\rho\gamma}(m^2_{\eta'} - m^2_{A'})^3$$
$$\times \frac{g^2_\rho}{(m^2_\rho - m^2_{A'})^2 + \Gamma^2_\rho m^2_\rho}. \qquad (11)$$

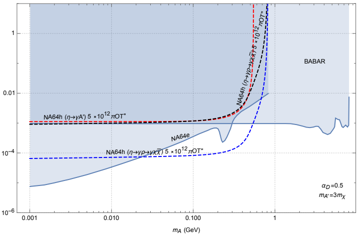
M. Benayoun et al.: Anomalous η/η' decays: the triangle and box anomalies

Table 3. η/η' Partial widths as predicted by the HLS model when switching on/off the box anomaly contribution. The significance is computed using an error obtained by adding in quadrature the experimental error and the relevant model error computed by Monte Carlo sampling (using information in Table 1)

Decay	PDG 2002	Prediction with box anomaly	Prediction without box anomaly
$\eta \to \pi^+\pi^-\gamma$ (eV)	55 ± 5	56.3 ± 1.7	100.9 ± 2.8
Significance (n σ)		0.25 σ	8 σ
$\eta' \to \pi^+\pi^-\gamma$ (keV)	60 ± 5	48.9 ± 3.9	57.5 ± 4.0
Significance (n σ)		1.75 σ	0.39 σ

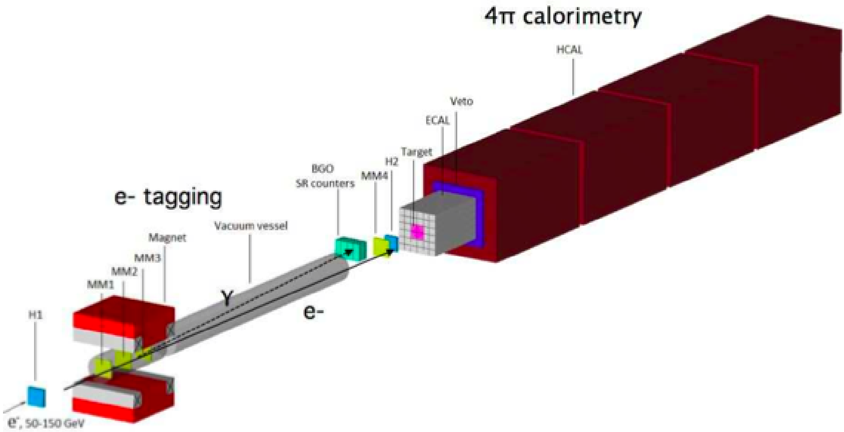
The differential decay width of $\eta' \to \gamma\chi\bar{\chi}$ with ρ meson resonance transition is

$$d\Gamma(\eta' \to (\rho^0 \to A' \to \chi\bar{\chi})\gamma) =$$
$$\frac{\alpha^2\epsilon^2\alpha_D}{6m^3_{\eta'}}(q^2 - m^2_{\eta'})^3(q^2 + 2m^2_\chi)(q^2 - 4m^2_\chi)^{\frac{1}{2}} \qquad (12)$$
$$\times \left[\frac{g^2_\rho}{(m^2_{A'} - q^2)^2 + \Gamma^2_{A'\to\bar{\chi}\chi} m^2_{A'}} \; \frac{g^2_{\eta'\rho\gamma}}{(m^2_\rho - q^2)^2 + \Gamma^2_\rho m^2_\rho}\right] \frac{dq^2}{\sqrt{q^2}}.$$

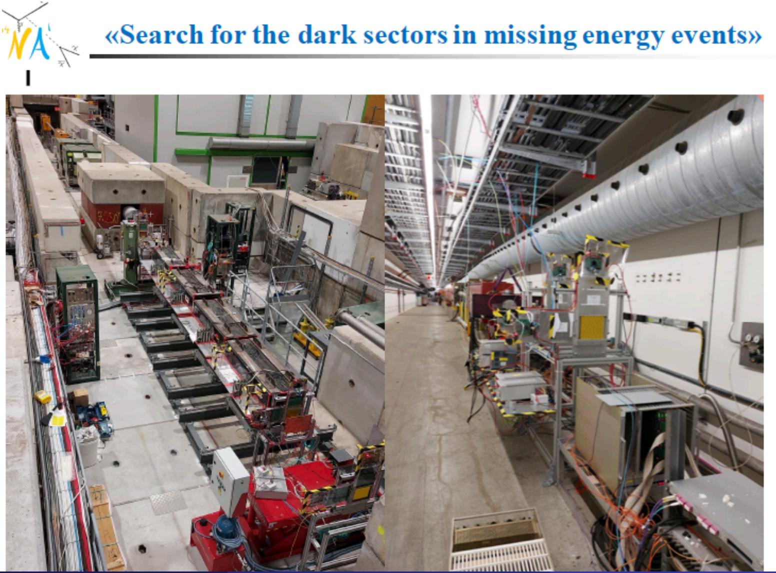


arXiv: 2312.01703

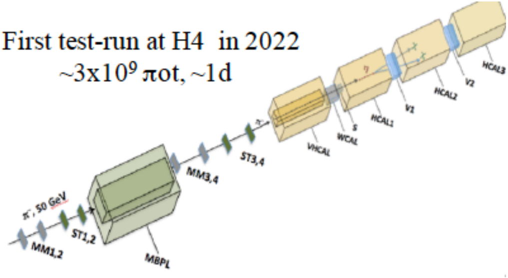
NA64

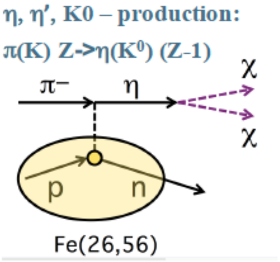

4π calorimetry
HCAL
Veto
ECAL
Target
H2
MM4
BGO
SR counters
e- tagging
Vacuum vessel
Magnet
MM3
MM2
MM1
H1
γ
e-
e⁻, 50-150 GeV

NA64



NA64


First test-run at H4 in 2022
~3x10^9 πot, ~1d
π⁻, 50 GeV
MM1,2
ST1,2
MBPL
MM3,4
ST3,4
VHCAL
WCAL
S
HCAL1
V1
HCAL2
V2
HCAL3


η, η′, K0 – production:
π(K) Z->η(K^0) (Z-1)
π−
η
χ
χ
p
n
Fe(26,56)

Bounds from collider physics

For pion beam we can generate pion from different processes.

- $\pi^- + (A, Z) \to \rho^0 + (A, Z)$
- Charge exchange reaction $\pi^- + (A, Z) \to M^0 + (A, Z)$

But we have a limit from experimental technology of search signal of DM.

The yield of meson in detector is

$$N_{M^0} \simeq \pi\mathrm{OT} \cdot \frac{\rho_T N_A}{A} L_T \, \sigma(\mathrm{mesonproduction}) \,, \tag{13}$$

$\mathrm{Br}(M^0 \to \mathrm{inv.}) \leq 2.3/N_{M^0}$ for invisible
and
$\mathrm{Br}(M^0 \to \mathrm{semi\text{-}inv.}) \leq 2.3/N_{M^0}$ for semi-invisible
at 90% confidence level (C.L.) assuming zero observed signal events and background-free case

Pion recharge process ($\pi^{\pm} + (A, Z) \to M^0 + (A, Z)$)

Differential cross section in case of the proton target is parameterized by experimental groups of Serpukhov-CERN:

$$\frac{d\sigma_H(s,t)}{dt} = \frac{d\sigma_H(s,t)}{dt}\bigg|_{t=0} \Big[1 - g(s)c(s)t\Big] \; \exp[c(s)t]\,, \tag{14}$$

where

$$\frac{d\sigma_H(s,t)}{dt}\bigg|_{t=0} = A\left(\frac{s}{s_0}\right)^{2\alpha_r(0)-2}, \tag{15}$$

A is the normalization factor, $g(s) = g_0 + g_1 \log(s/s_0)$ and $c(s) = c_0 + c_1 \log(s/s_0)$ are the s-running couplings.
For the integral cross section in case of the proton target we get

$$\sigma_H(s) = A\left(\frac{s}{s_0}\right)^{2\alpha_r(0)-2} \frac{1+g(s)}{c(s)}\,. \tag{16}$$

Extension to arbitrary nuclei N with charge Z is normally done by multiplying with factor $Z^{2/3}$. However, we found that this behavior should be slightly corrected as $Z^{2/3-0.15Z^{-2/3}}$. I.e. the integral cross section for the neutral meson production at nuclei with charge Z reads:

$$\sigma_N(s) = \sigma_H(s)\, Z^{2/3-0.15Z^{-2/3}}\,. \tag{17}$$

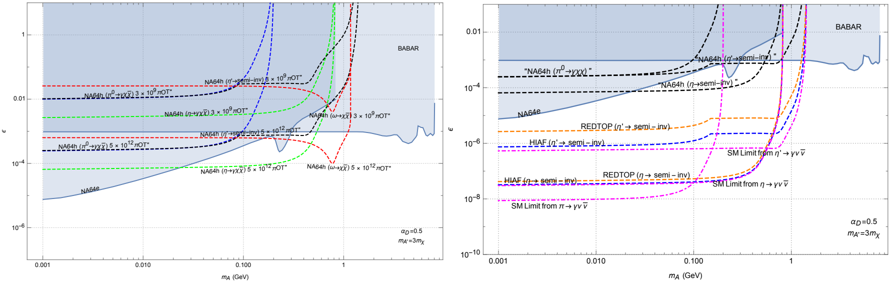
Predictions for the integral cross sections for the $\pi^- + (A, Z) \to M^0 + (A, Z-1)$ reactions at beam momentum $P = 50$ GeV in μb units.

Meson	H	Li	Be	C	Al	Fe
π^0	8.1 ± 1.4	15.6 ± 2.6	18.8 ± 3.1	24.7 ± 4.1	41.9 ± 6.8	67.4 ± 11
η	2.6 ± 0.9	5.1 ± 1.7	6.1 ± 2.1	8.0 ± 2.8	13.6 ± 4.7	21.9 ± 7.5
η'	1.3 ± 0.4	2.4 ± 0.8	2.9 ± 1.0	3.8 ± 1.3	6.5 ± 2.1	10.4 ± 3.5
ω	2.0 ± 0.7	3.9 ± 1.2	4.7 ± 1.5	6.2 ± 1.9	10.5 ± 3.2	16.9 ± 5.1
f_2	2.1 ± 0.8	4.0 ± 1.5	4.8 ± 1.9	6.3 ± 2.4	10.6 ± 4.2	17.1 ± 6.7

Predictions for the integral cross sections for the $\pi^- + (A, Z) \to P^0(\to 2\gamma) + (A, Z-1)$, $\pi^- + (A, Z) \to \omega(\to \pi^0\gamma) + (A, Z-1)$, and $\pi^- + (A, Z) \to f_2(\to 2\pi^0) + (A, Z-1)$, reactions at beam momentum $P = 50$ GeV in μb units. Here $P^0 = \pi^0, \eta, \eta'$.

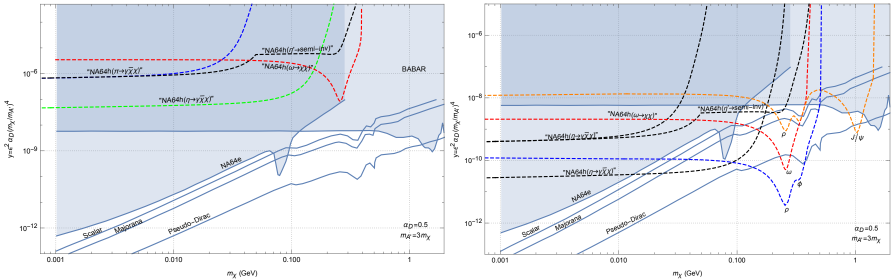
Meson	H	Li	Be	C	Al	Fe
π^0	8.1 ± 1.4	15.6 ± 2.6	18.8 ± 3.1	24.7 ± 4.1	41.9 ± 6.8	67.4 ± 11
η	1.0 ± 0.4	2.0 ± 0.7	2.4 ± 0.8	3.2 ± 1.0	5.4 ± 1.8	8.6 ± 3.0
η'	0.03 ± 0.01	0.06 ± 0.01	0.07 ± 0.03	0.09 ± 0.03	0.15 ± 0.05	0.24 ± 0.08
ω	0.17 ± 0.05	0.33 ± 0.10	0.39 ± 0.12	0.52 ± 0.15	0.87 ± 0.27	1.41 ± 0.43
f_2	0.58 ± 0.23	1.11 ± 0.44	1.34 ± 0.53	1.76 ± 0.69	2.98 ± 1.18	4.80 ± 1.89

Bound to dark photon / ϵ mixing parameter



Bounds for dark photon ϵ parameter mixing obtained for 90% C.L. and for case where $m_{A'} = 3m_\chi$ and $\alpha_D = 0.5$. At both panels, we show existed limit from current data of NA64$_e$ experiment and constraints from production of DM in e^+e^- collision at BABAR. Top panel: Bounds from semi-invisible pseudoscalar decays ($\pi^0 \to \gamma\chi\bar{\chi}$, $\eta \to \gamma\chi\bar{\chi}$, $\eta' \to semi - inv$) and invisible decay ($\omega \to \chi\bar{\chi}$) for statistics 3×10^9 πOT (few days of data taking) and for 5×10^{12} πOT as proposal statistics for NA64$_h$ experiment. Bottom panel: Bounds from semi-invisible pseudoscalar decays ($\pi^0 \to \gamma\chi\bar{\chi}$, $\eta \to \gamma\chi\bar{\chi}$, $\eta' \to \gamma\chi\bar{\chi}$) for proposal/projected statistics of NA64$_h$, REDTOP and HIAF experiments. The dot-dashed lines show limit of neutrino floor from decay light pseudoscalar mesons to $\gamma\nu\bar{\nu}$ predicted in the framework of SM.

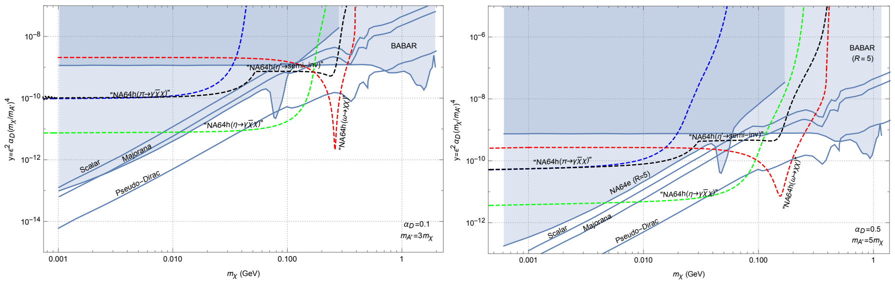
arxiv: 2312.01703



Right panel: limits from semi-invisible pseudoscalar decays ($\pi^0 \to \gamma\chi\bar{\chi}$, $\eta \to \gamma\chi\bar{\chi}$, $\eta' \to semi - inv$) and invisible decay ($\omega \to \chi\bar{\chi}$) using statistics 3×10^9 πOT. Left panel: Limits for the same decays for 5×10^{12} πOT of $NA64_h$ experiment in comparison with bound from invisible vector meson decays obtained for $NA64_e$ and LDMX experiments [Schuster:2021].

arxiv: 2312.01703

Bound to dark photon (different $R = m_{A'}/m_\chi$ and α_D)



The projected 90% C.L. exclusion for benchmark scenarios of invisible and semi-invisible neutral meson decays to dark matter in dark photon mediator portal model. At both panels, we show existed limit from last data of NA64$_e$ experiment and constraints from production of DM in e^+e^- collision at BABAR and limits from invisible pseudoscalar decays ($\pi^0 \to \gamma\chi\bar{\chi}$, $\eta \to \gamma\chi\bar{\chi}$, $\eta' \to semi - inv$) and invisible decay ($\omega \to \chi\bar{\chi}$) using statistics 5×10^{12} πOT. Right panel: for parameter $\alpha_D = 0.1$ and $m_{A'} = 3m_\chi$. Left panel: for parameter $\alpha_D = 0.5$ and $m_{A'} = 5m_\chi$.

arxiv: 2312.01703

Conclusion

- Meson charge exchange reaction on of possible processes which can be used for analysis DM model parameter space by using missing energy/momentum technique.
- Intermediate vector state should take into account for analyze of decay of η and η' mesons into dark.
- Using projected statistics for the neutral meson yield in the NA64, we can predict the typical bound on the semi-invisible on the invisible branching ratio

$$\begin{aligned} \mathrm{Br}(\pi^0 \to \gamma + A') &< 3.16 \times 10^{-9} \quad (\text{from NA64}_h); \\ \mathrm{Br}(\eta \to semi - inv) &< 9.4 \times 10^{-9} \quad (\text{from NA64}_h); \\ \mathrm{Br}(\eta' \to semi - inv) &< 4.7 \times 10^{-9} \quad (\text{from NA64}_h); \\ \mathrm{Br}(\omega \to \text{inv.}) &< 8.1 \times 10^{-9} \quad (\text{from NA64}_h); \end{aligned}$$

- Low energy pion beams are more suitable for test of DM physics by missing energy experimental search technique from light meson decays.

Thank your for you attention!